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Thermal Analysis and Microhardness Mapping in Hybrid Laser Welds in a Structural Steel

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Abstract. Hybrid welding, the combination of laser and arc welding, is being heavily investigated for potential applications in the fabrication of structural steel components. The hybrid process is an alternative to autogenous laser welding that requires good fit-up of the parts. With the hybrid process, the addition of filler metal alters the weld pass chemistry and fills any gaps that may occur. In some applications, the fit-up of parts is only part of the issue for laser welding. In some structural steel components, the chemistry of the base metal when autogenously laser welded can result in weldments (weld metal and heat-affected zone (HAZ)) that have high hardness values. This indirectly indicates that the weld metal is brittle and not suitable for certain applications. The hardness values of the weldment have been used as an acceptance criteria for certain industrial applications. The use of hybrid welding may address the hardness issue. The addition of filler metal through a gas metal arc (GMAW) based hybrid process decrease the cooling rate in the HAZ therefore improving mechanical properties. These improvements can often be detected by microhardness profiles. While traditional hardness profiles tabulate hardness in a few regions of the weld, hardness mapping better profiles the hardness trends in the weldment. This paper will present welding results for the hybrid structural welding of a structural carbon steel using a 4 kW Nd:YAG based hybrid laser system. The data will center on the thermal response of the steel to the welding process, on the hardness mapping of the weldments and how the heat input altered the hardness and the mechanical properties of the welds.

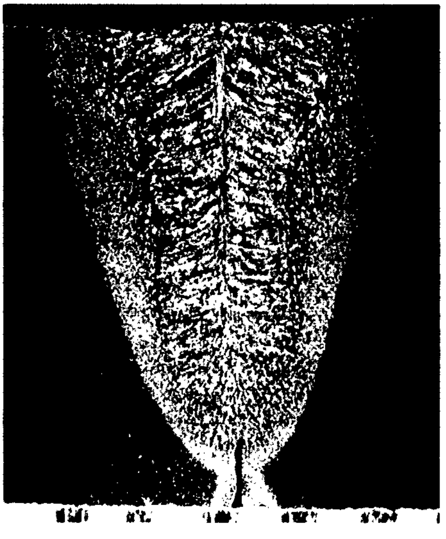
Introduction

The concept of combining a laser welding system with a conventional arc welding system (GTAW) was first proposed by Steen [1] in order to improve the stability of the laser welding system and to allow greater flexibility in part fit-up. Several papers [2,3] were presented at the annual meeting of the International Institute of Welding in Copenhagen in 2002. Ishide et al [2] stated that using a YAG laser at a power of 3 kW they were able to hybrid laser weld a 4 mm thick aluminum alloy at a speed of 4 m/min. For a mild steel plate they realized butt welding at 1 m/min with 5 kW of 6mm thick plate. Just as significantly as the weld speed was their ability to hybrid laser weld with gaps up to 1.5mm in a plate 6mm thick. Dilthey [3] stated that the GMAW laser hybrid process can increase the gap bridging ability, i. e. it appreciably broadens the range of tolerances with regard to edge preparation quality. The arc's energy input in the hybrid welding process also permits control of the cooling conditions. Via the keyhole the laser beam brings about easier ignition of the arc, stabilization of the arc welding process, and penetration of the energy deep into the material. The improvement of the energy input leads to a greater welding depth and speed being achieved with the hybrid process compared with individual processes on their own. An example was given of welding 5mm thick AH36 steel with a YAG laser at 6 kW and a GMAW input energy of 274 kJ/m at a speed of 4.1 m/min.

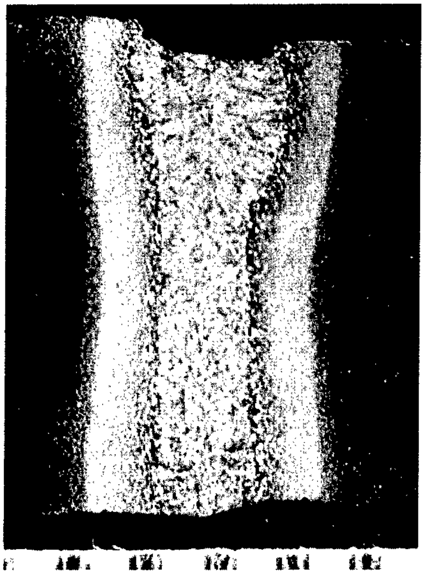
Thus the hybrid laser process offers significant economic advantages in terms of welding speed with respect to the conventional GMAW or GTAW processes without the need for very close fit-up. This paper will compare an autogenous laser weld to a hybrid laser weld in a 6.3mm thick structural steel called HSLA-65. The paper will present a thermal analysis for both welds based on a constrained optimization technique. The results of that technique allow us to extract cooling curves at any point in the weld. The cooling curves are then combined with the chemical composition in order to calculate the volume fractions of microstructures and their hardness. Experimentally we mapped the hardness over the entire weld. We compare the experimental results to the calculations and comment on their meaning.

Thermal Model

As discussed more extensively [4], motivation for our thermal model is the fact that the inherent complexity of welding processes implies that a completely first-principles approach, i.e., a model representation which attempts to include all underlying physical processes, to the calculation of thermal histories may not be well posed in general for quantitative analysis. Experience has shown this to be especially true for the calculation of thermal histories in the heat-affected-zone (HAZ). Following our approach the entire fusion line of the weld was used as input for the thermal model, which uses a constrained optimization process [5,6]. That is to say, input for the thermal model is effected via the specification of constraint conditions: defined according to experimental information concerning solidification cross sections. Macrographs showing the cross section of the welds are presented in Fig. 1.



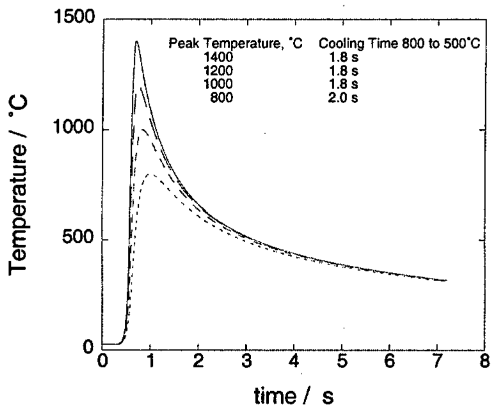
a)Hybrid laser weld



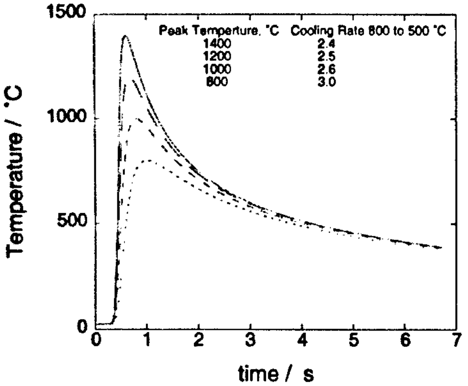
b) Autogenous laser weld

Fig. 1 Cross sections of the autogenous and laser hybrid welds.

The thermal model allows us to extract the cooling curves at any point in the weld. The cooling curves shown in Fig. 2 were taken at the same z-value (thickness) and at increasing y values (width). These curves indicate that the cooling time from 800 to 500 ˚C is independent of peak temperature and thus dependent only on the thermal properties of the steel.



(a) autogenous laser weld



(b) hybrid laser weld

Fig. 2 Cooling curves for the autogenous (a) and hybrid (b) laser welds

Experiment

An autogenous laser beam weld was fabricated in 6.3mm thick HSLA-65 steel at a Nd:YAG laser power of 4 kW and a welding speed of 0.63 m/min. The corresponding hybrid laser weld was fabricated at the same power and a welding speed of 0.89 m/min. The GMAW had a voltage setting of 26.8 volts, a current setting of 190 amps and a wire speed of 17.3 m/min with a gas shielding of 90 Argon – 10% CO_2. The plates were butted against each other without any gap. The chemistry of the plate and the as-deposited weld metal is given in Table 1.

Table 1 Compositions of plate and weld

	C	Mn	Si	S	P	Cu
HSLA-65	0.083	1.19	0.22	0.005	0.013	0.04
Weld	0.09	1.28	0.76	0.010	0.009	0.12

Based on the composition, the cooling curves and a prior austenite grain size, the volume fractions of the daughter products of the austenite decomposition have been determined [7]. The results of this calculation indicate that the microstructure is 99% martensite for both welds. The microstructure of the autogenous weld has a calculated hardness of 348 HV, whereas the hardness of the hybrid laser weld has a calculated hardness of 365 HV.

The hardness of both welds was mapped over the entire weld (base plate, HAZ, and fusion zone) at incremental steps of 0.25mm using an automated hardness indenter. The resulting maps and a hardness scale are shown in Fig. 3. The maximum hardness measured in the autogenous weld was 360 HV, whereas in the hybrid laser weld the maximum hardness was 388 HV.

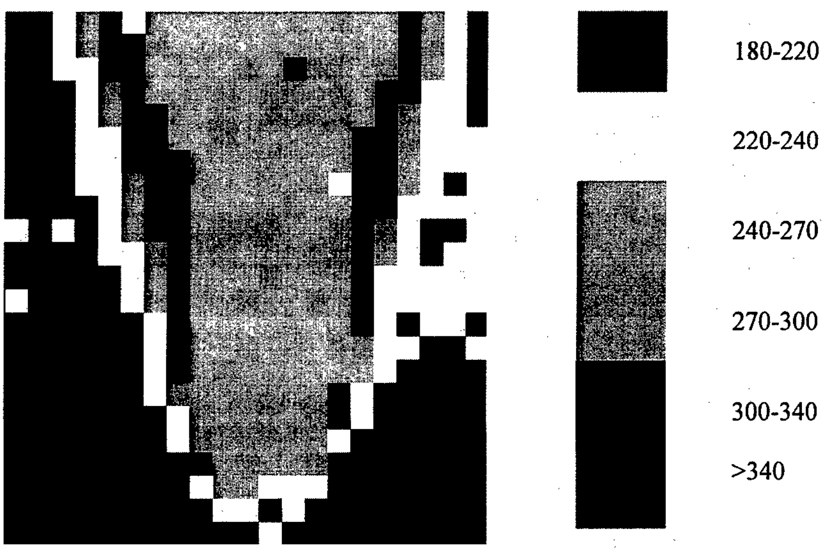
Discussion

The combination of a martensitic microstructure and a high hardness in a marine environment is an invitation to subcritical cracking through the effect of hydrogen. Stout and Doty [8] state that susceptibility to underbead cracking in a longitudinally sectioned, bead-welded specimen was correlated to field-welding experience at a hardness level greater than 250 HVN. They further state that "any steel, welded under specified conditions, that failed at a bend angle below 20 degrees in a room temperature test was assumed to be unsatisfactory for service in the as-welded condition". Their accompanying graph indicates that a bend angle of 20 degrees correlates to a hardness of 250 HVN. Bailey [9], who has written extensively about hydrogen cracking in steels and how to weld without hydrogen cracking, does not assign a "critical hardness" which should not be exceeded in the welding of steels. However he cautions that HAZ and weld metal hardness have been related to the risk of hydrogen cracking. Lloyd's Register has issued draft guidelines for laser welding and state that 350 HV should not be exceeded. Although for autogenous welds or using low hydrogen consumables, values less than or equal to 380 HV will be considered acceptable.

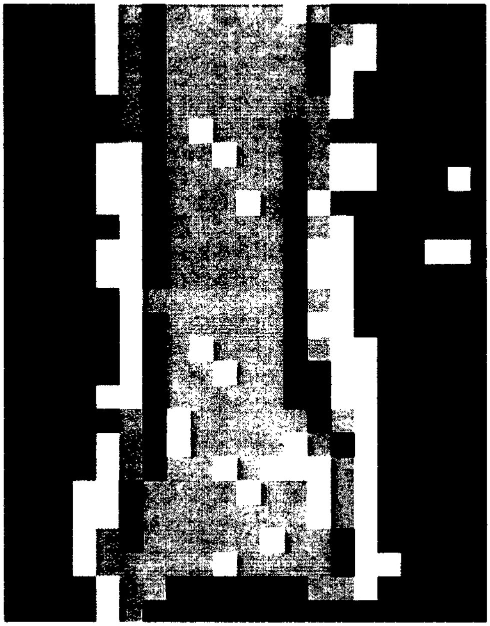
The maps indicate significant areas in the fusion and HAZ where the hardness exceeds 350 HV. The addition of filler metal does not necessarily modify the cooling rate sufficiently to alleviate the high hardness associated with the formation of martensite. This is especially true when the carbon content of the consumable is greater than the carbon content of the base plate.

Conclusion

Laser hybrid welding permits gaps in the joint which are unacceptable with autogenous laser welding. The selection of the consumable must be done with great care since the hardness of the hybrid laser weld can be greater that that of the autogenous laser weld.



a) Hybrid laser weld



b) Autogenous laser weld

Fig. 3 Hardness maps of hybrid and autogenous laser welds

Acknowledgements

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